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Lighter structures for transports: The role of innovation in metallurgy

Allègement des structures dans les transports : le rôle de l'innovation en métallurgie

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A B S T R A C T

The landscape of energy production and use is facing great challenges in the transportation sectors. The two main means of transportation, automobiles and airplanes, are mainly made from metals. The necessity of reducing their carbon emission translates into major stakes for weight reduction, which can only be the result of an interplay between improving the alloys and the part's geometry. This contribution discusses some of the strategies for structural weight reduction based on innovative alloy design in aluminum alloys and steels and on innovative processing by additive manufacturing.

R É S U M É

Le paysage de la production d'énergie et de son utilisation est confronté à des défis importants dans le secteur des transports. Les deux principaux moyens de transport, automobile et aérien, sont principalement fabriqués avec des métaux. La nécessité de réduire leurs émissions de CO_2 se traduit par une exigence majeure d'allègement, qui ne peut résulter que d'une action conjuguée d'amélioration des alliages et de la géométrie des pièces. Cette contribution discute certaines des stratégies pour l'allègement des structures basées sur la conception innovante d'alliages d'aluminium et d'aciers et sur les procédés innovants par fabrication additive.

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1. Introduction

This contribution is part of a thematic volume of the *Comptes rendus Physique*: "The energy of tomorrow". Dealing with our use of energy requires thinking both on energy conversion to a usable energy for society's needs, and on energy use in

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the many devices that we are using in everyday life. Among these, one key issue to improve the footprint of our society is to reduce the emissions of greenhouse gas by the main means of transportations, primarily cars and airplanes, as well as the embedded energy [1]. This requirement seems obvious; however, the ways to get there are not straightforward, especially when cost constraints are taken into account.

Reducing the impact of transports requires an approach towards several directions. The engines must be further optimized, and shift to different energy sources can bring improvements (fully electric, hybrid or hydrogen cars, for instance). However, if vehicles using different sources of energy can be an efficient way to link them to renewable energy sources, or more generally to low-carbon energy, it is not by itself necessarily a good way to reduce the total amount of energy used in transports.

A common target to all transport means is to reduce the weight of the structures [2,3]. By itself, weight reduction is an effective way to reduce the consumption of vehicles per transported passenger. This is particularly true for airplanes and for cars as well, as soon as they travel at non-constant speed. It has to be pointed out that this target becomes somewhat less effective with electric cars where some of the energy of breaking serves to charge back the battery. In fact, while the weight of airplanes per passenger transported has effectively been reduced in the last decades by an improvement in the design and materials used, this is not so true for cars, for which the weight has increased for a long time [4] while a tendency for slow decrease is now slowly arriving. This tendency for making ever heavier cars has been driven by the improvement of comfort and safety, which required the addition of extra weight.

Reducing the weight of a car or an airplane is actually more important than what can be predicted from simply this weight reduction [3,5]. When the weight of the structure is reduced, synergetic effects arise: the engine can be smaller, which reduces its own weight and also reduces consumption. And all other elements can also be designed at lower weight: brakes, suspensions, etc. Such synergetic effects were key to the major shift that was made by the car industry in the USA when Ford decided to make their F150 pickup truck (one of the most sold cars in the USA) entirely of aluminum. This decision made it possible to reduce substantially the engine's size and therefore the truck's gas intake. Obviously, it remains high compared to that of small cars. Therefore, weight reduction has been recognized as a key way to achieve ambitious emission reduction programs such as the target for 2 l/100 km cars in France.

Interestingly, it has been recognized since a very long time that reducing alone the price of using transportation means (which would be a side-effect of reducing consumption) does not necessarily mean that the global emissions will decrease. The contrary can be observed and is known since 1865 as Jevon's paradox [6], from the name of a British economist, William Stanley Jevons, who recognized that an improvement of efficiency could be compensated by an increase in demand due to the reduced cost of the service. Typically, such a mechanism can be observed in the aerospace industry, where from the 1970s to now the consumption of airplanes per passenger per 100 km travelled has gone down by a factor of two (7 l to 3.5 l, approximately), and yet the total consumption of airplanes has increased drastically because of the development of low-cost air transport, which itself has been made possible by the availability of low-consumption airplanes. Therefore, it becomes quite clear that making lighter means of transportation (and more generally, making them more economic to use) cannot alone guarantee a lowering of the total emissions of transport, and the legal framework must be adapted simultaneously (restriction policies) [7].

Improving the weight of structures is a never-ending interplay between material properties and structural design. In this contribution, we will restrict ourselves to the metallic subset of materials used in the transport sector. Traditionally, these two areas were relatively separate: the material's supplier would provide a material with a set of properties, and the designer would try to make the most out of them. However, such a separation is nowadays outdated, because the development of new alloys needs to take into account the complexity of the property sets required for each application. Nowadays, each part of a car or an airplane, submitted to different combinations of mechanical loading and environmental constraints (temperature, corrosive agents), should have a different optimal set of properties, which should lead to a specific material design. Consequently, the diversity of the alloys used in transports has dramatically increased, and to reach this goal the material's producer and the material's user need to work in close collaboration, so that new materials match the property sets required by new applications.

More recently, the development of additive manufacturing in the metallurgy community has led to another paradigm shift: in this case, the material and the structure are only one single concept, which needs to be optimized as a whole: changing the structure of an additive manufactured part requires changes in processing parameters that necessarily impact the material's properties.

In the following, we will present a few examples of how material's research and innovation can lead to improved sets of material properties and architectures. First, we will present some aspects of the development of the new family of Al–Cu–Li alloys for aerospace applications; secondly, we will present the progress brought by the new generations of high-strength steels under development for automotive applications; thirdly, we will present some of the benefits and challenges of metal additive manufacturing using a fast-developing methods, namely Electron Beam Melting.

2. Al–Cu–Li alloys for aerospace applications

The construction of airplanes relies, since the beginning of the 20th century, largely on the use of aluminum alloys, since the discovery by A. Wilm of age hardening brought by alloying soft aluminum by Cu atoms (see [8] for a historical perspective). At that time, age-hardened aluminum alloys with improved strength were rapidly used in industrial appli-

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